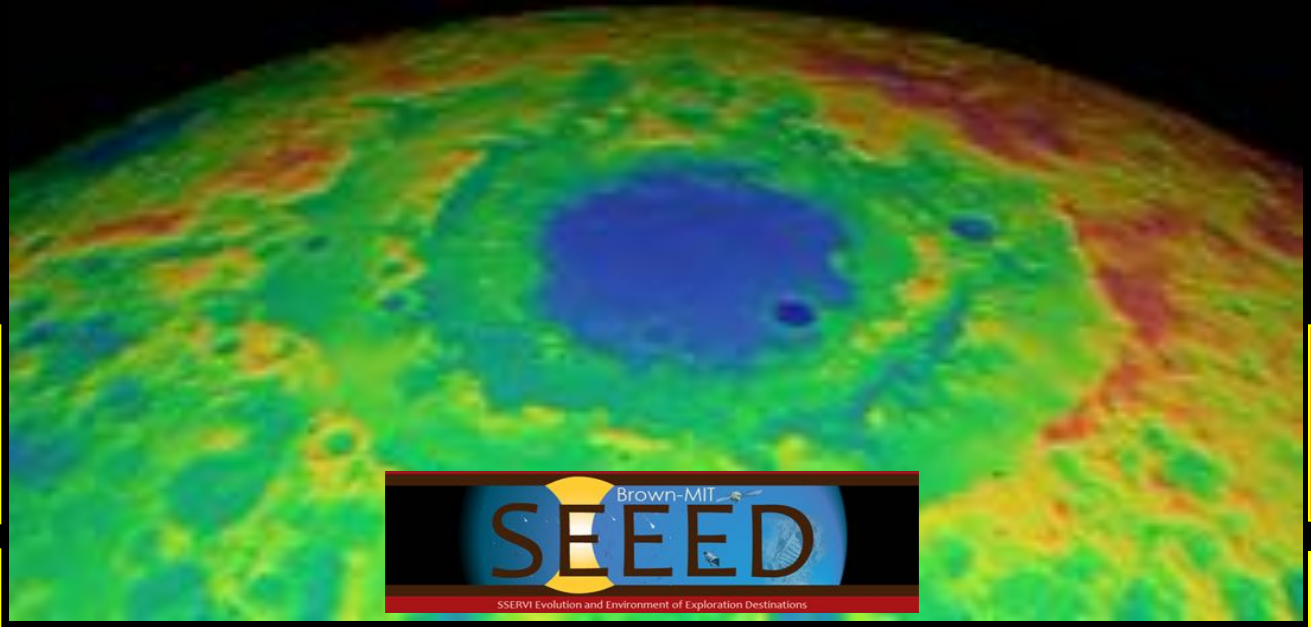
# A Human/Robotic Exploration Design Reference Campaign Architecture: Opportunities for Commercial Missions




James Head, Carle Pieters, David Scott, Brandon Johnson, Ross Potter: Brown Univ., Providence, RI USA
Jeffrey Hoffman: MIT, Cambridge, MA USA
Bernard Foing: ESA ESTEC, Noordwijk, The Netherlands
Lev Zelenyi, Igor Mitrofanov: Institute for Space Research, RAS, Moscow, Russia
Mikhail Marov, Alexander Basilevsky, Mikhail Ivanov: Vernadsky Institute, RAS, Moscow, Russia
Ralf Jaumann, DLR Institute of Planetary Research, Berlin, Germany
Long Xiao: China University of Geosciences, Wuhan, Hubei, China
Junichi Haruyama, Makiko Ohtake: ISAS, JAXA, Sagamihara, Japan
P. Senthil Kumar: CSIR-NGRI, Hyderabad, India
Oded Aharonson: Weizmann Institute, Rehovot, Israel

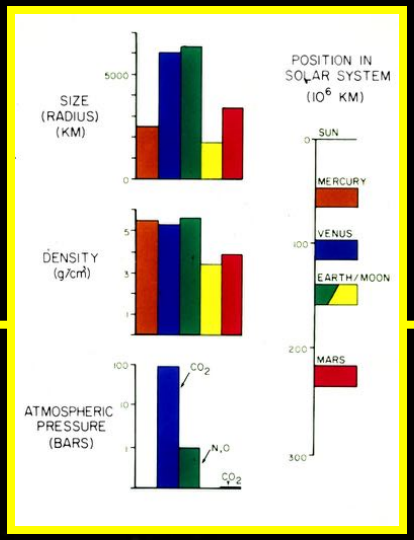
# Apollo Lunar Exploration Program:
# Six Scientific Expeditions to the Moon




Established the Moon as a Cornerstone for Solar System Science



# The Moon as a Cornerstone for Solar System Science

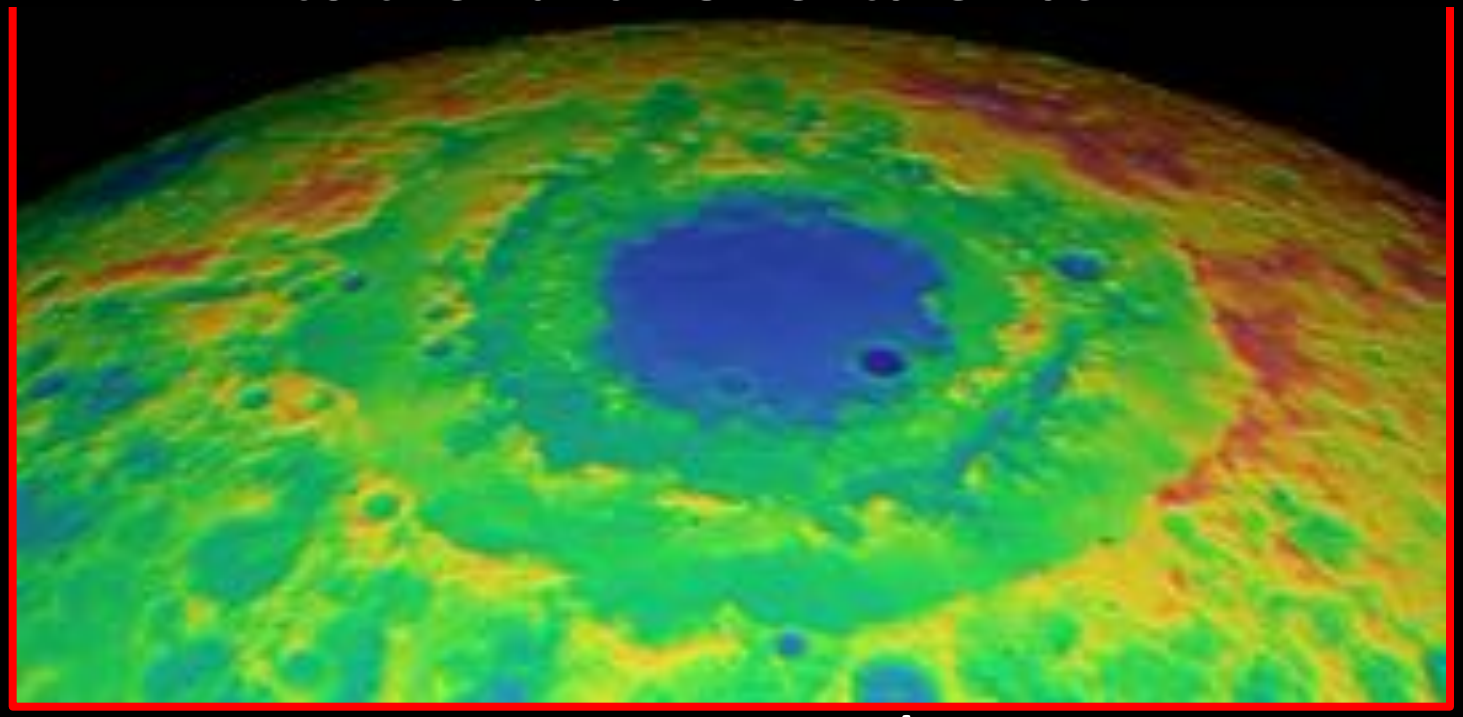



-One or more spacecraft currently/recently orbiting each of the terrestrial planets.

-We have fundamental questions about the formation and evolution of each of these planetary bodies, and together the terrestrial planetary bodies as a whole.

-Many of these questions can only be answered in the context of lunar exploration

# Exploration of Planetary Crusts: A Human/Robotic Exploration Design Reference Campaign to the Lunar Orientale Basin



1. The importance of coordinated human/robotic exploration.
2. Why the Orientale multi-ring basin?
3. Human/Robotic Scientific Destinations at Orientale.
4. The Human/Robotic Architecture: A Basis for Design Reference Missions.

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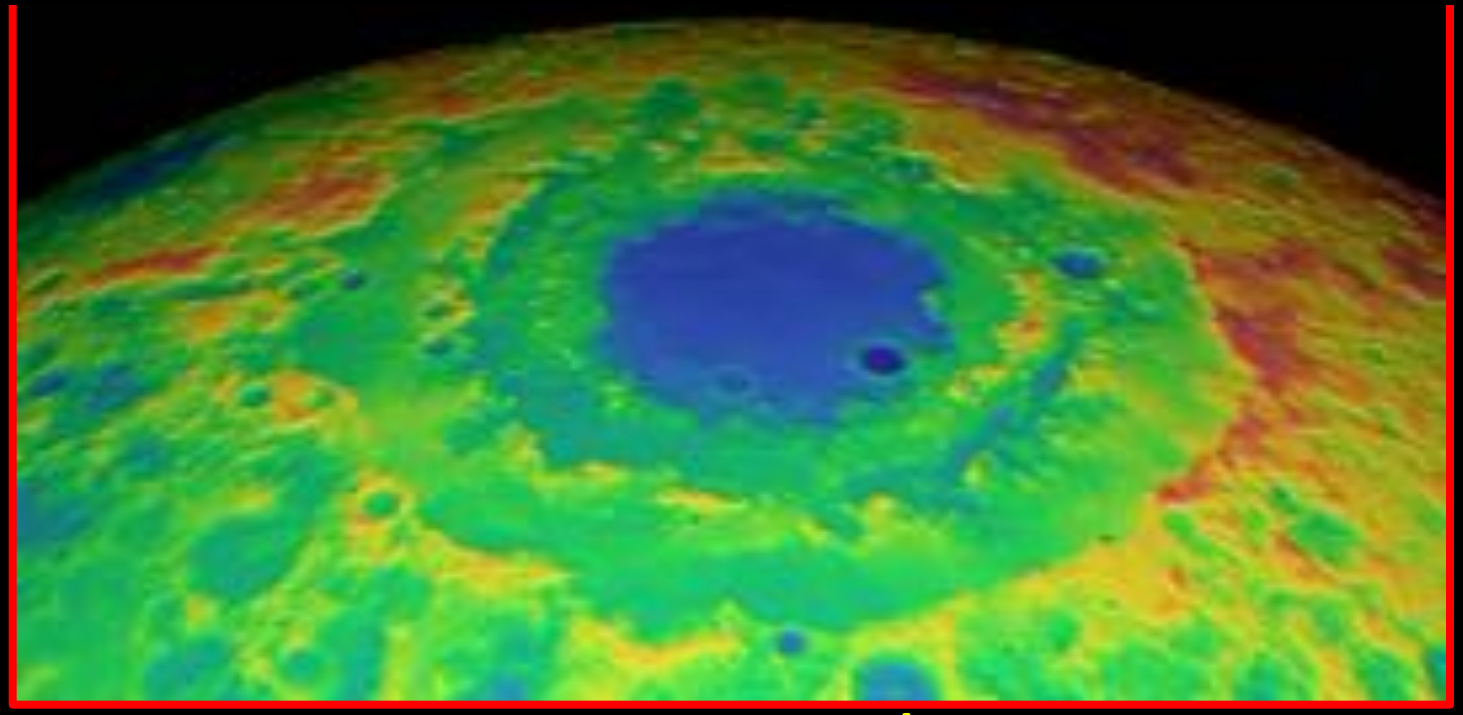

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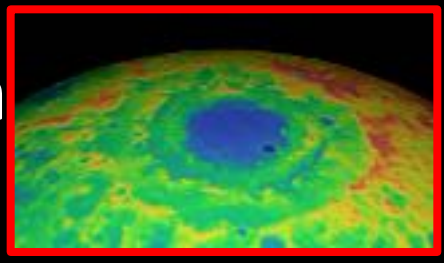
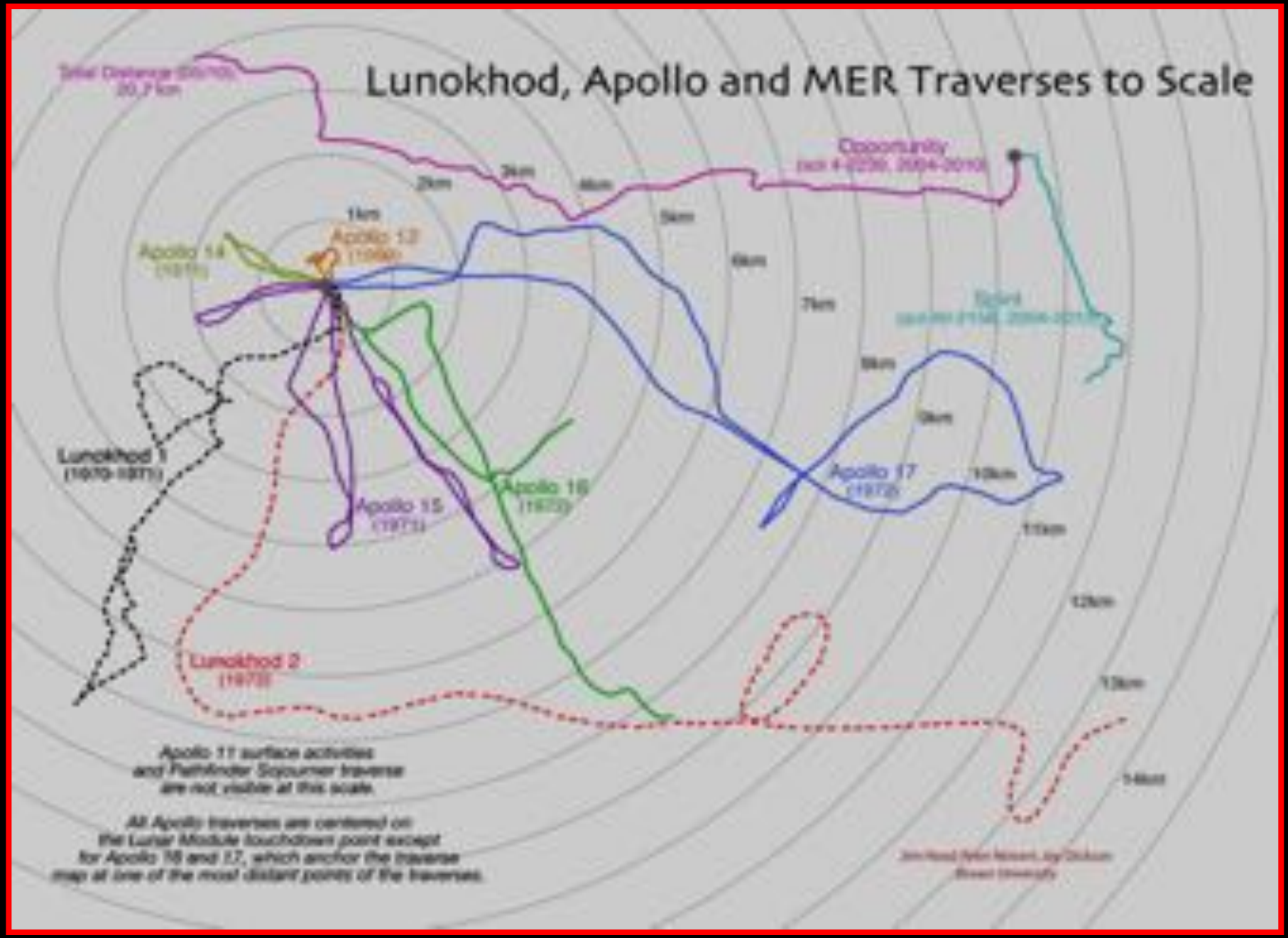
# Human/Robotic Exploration Optimization Centers on Six Themes

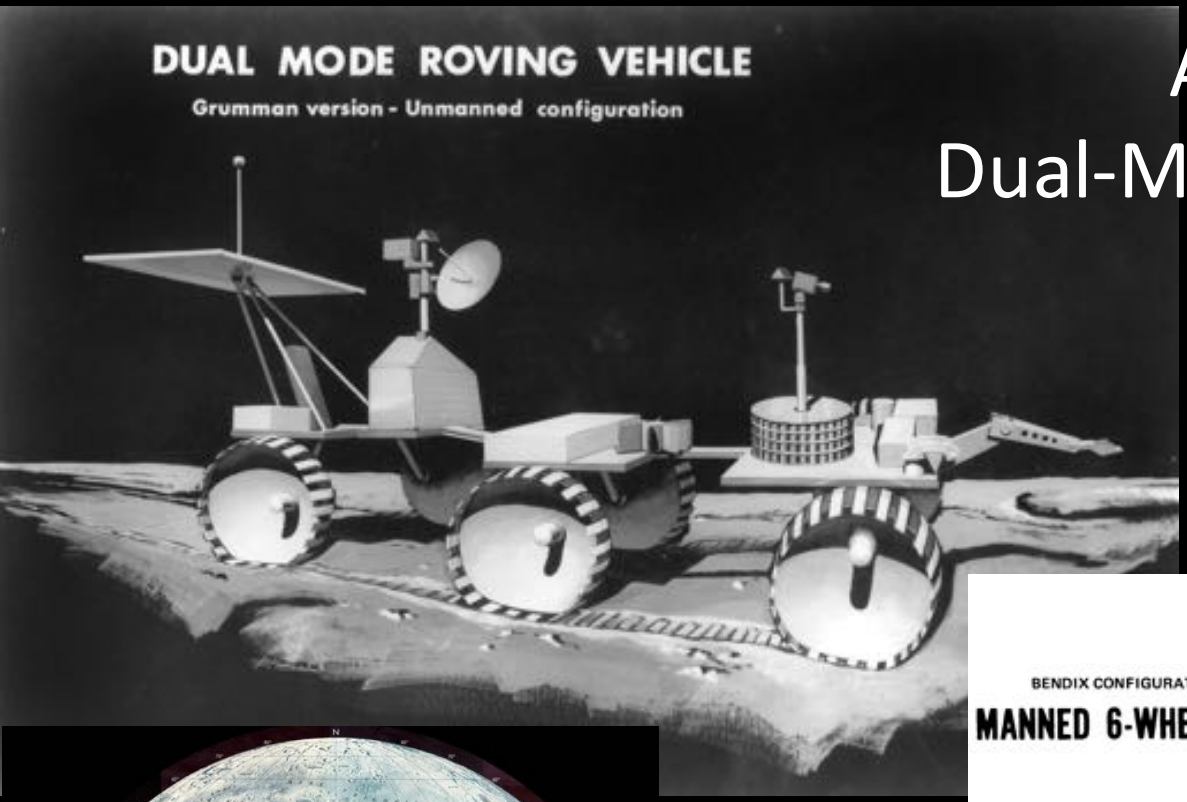


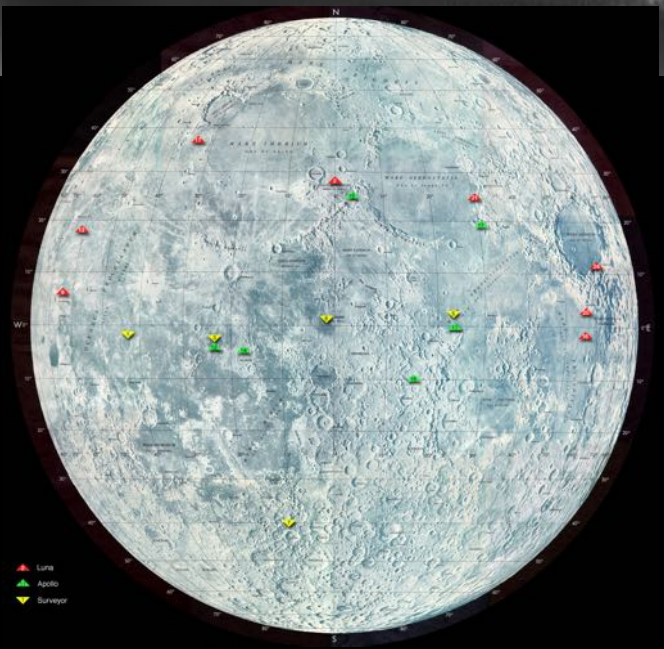
- I) *Precursor* (What do we need to know before we send humans?).
- II) *Context* (What are the robotic mission requirements for final landing site selection and regional context for landing site results?).
- III) *Infrastructure/Operations* (What specific robotic capabilities are required to optimize human scientific exploration performance?).
- IV) *Interpolation* (How do we use robotic missions to interpolate between human traverses?).
- V) *Extrapolation* (How do we use robotic missions to extrapolate beyond the human exploration radius?).
- VI) *Progeny* (What targeted robotic successor missions might be sent to the region to follow up on discoveries during exploration and from post-campaign analysis?).

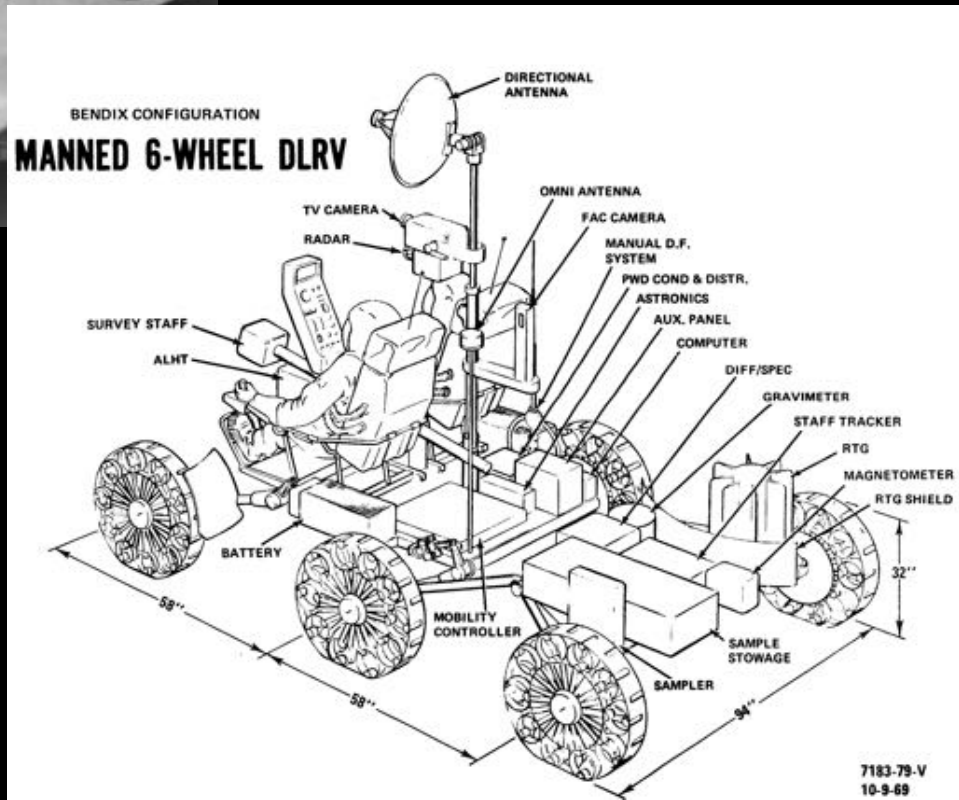
# What is the Relationship of Human and Robotic Exploration?



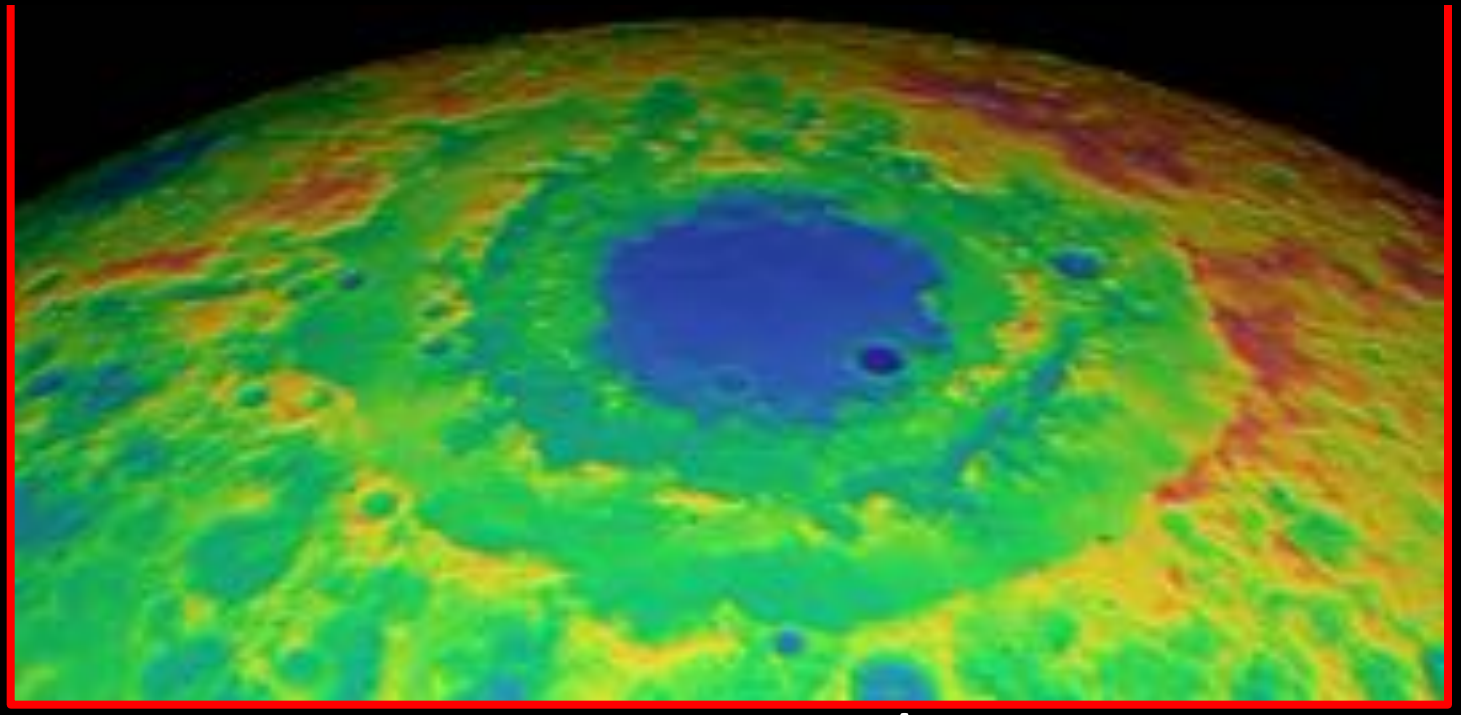
# Apollo 19-21
# Dual-Mode Roving Vehicle



# Exploration of Planetary Crusts: A Human/Robotic Exploration Design Reference Campaign to the Lunar Orientale Basin



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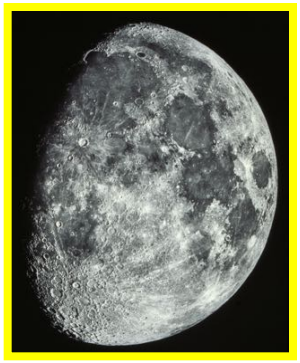
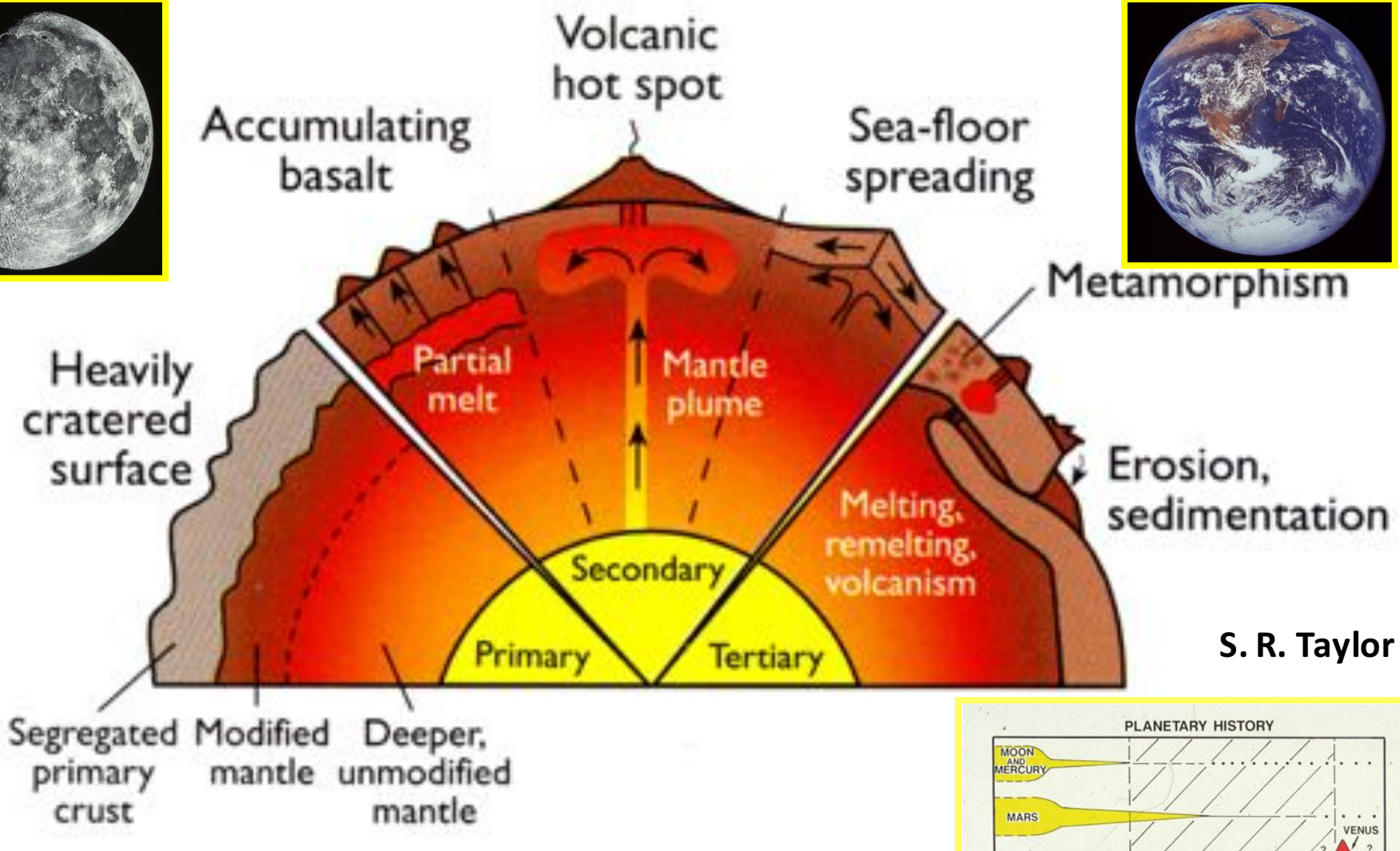
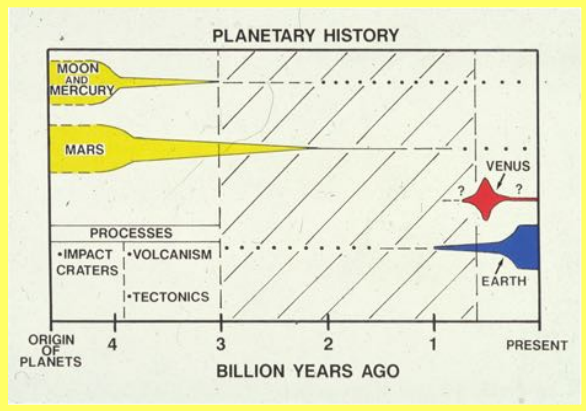
# Formation and Evolution of Planetary Crusts



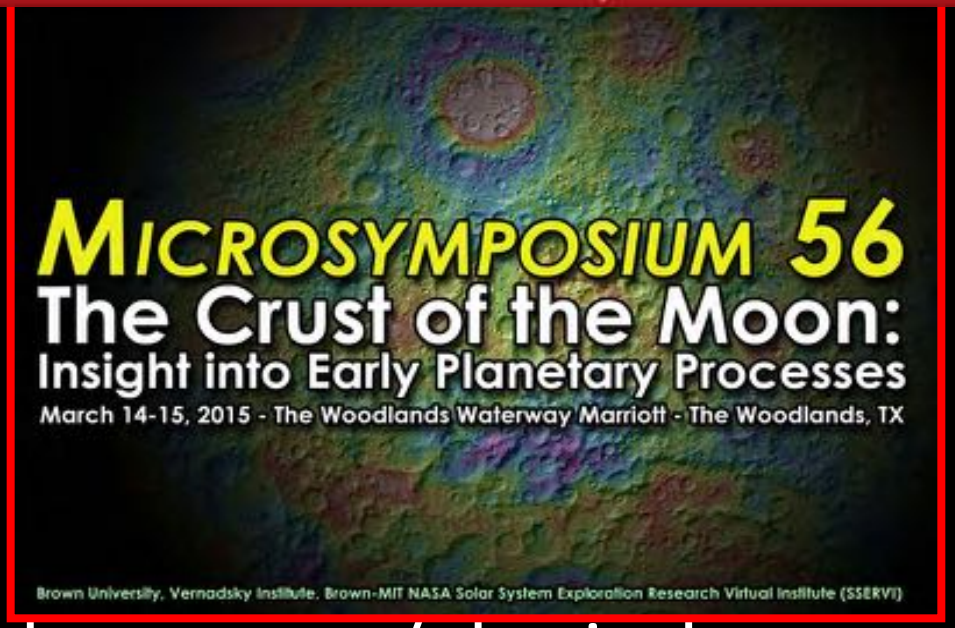


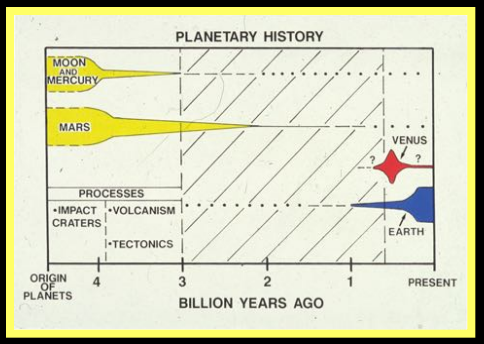



**S. R. Taylor**



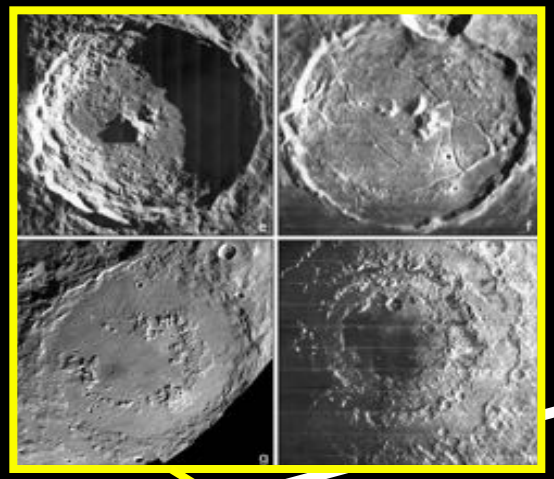

**The Moon is a Laboratory for the Study of Primary and Secondary Crusts in Early Planetary History.**




- 1. Crustal geometry/physical structure
- 2. Crustal chemistry/mineralogy/petrology;
- 3. Exogenic crustal modification by impacts;
- 4. Chronology of crustal formation/evolution.

# Major Lunar Features: Multi-ring basins:




Fresh Crater Characteristics

Crater Depth (km)

4
3
2
1

Terraces
Central peak
Polygonal outline
Flat floor
Swirl
Bowl shaped
Circular rim

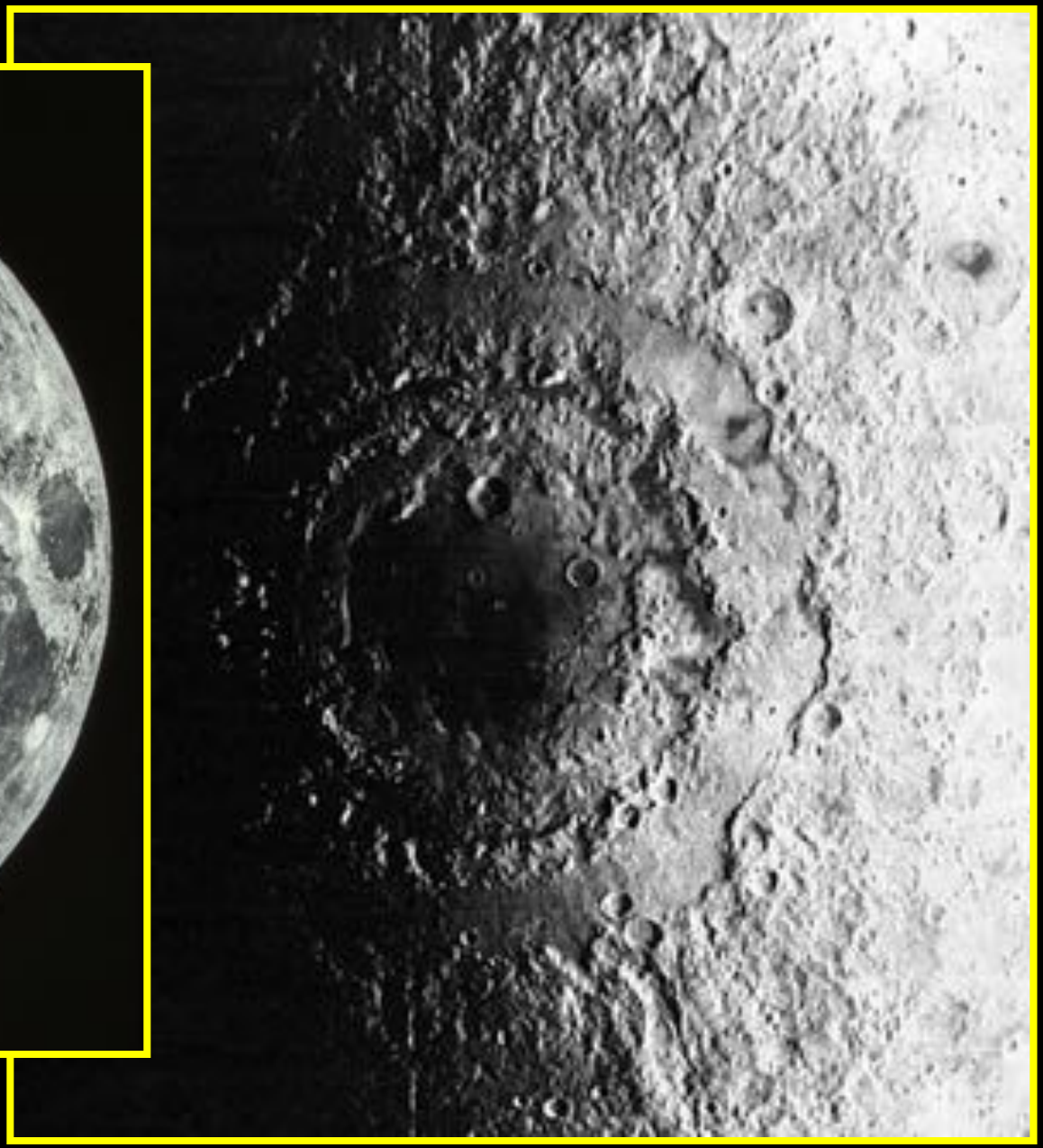
What about the transition to Peak-Ring Basins?

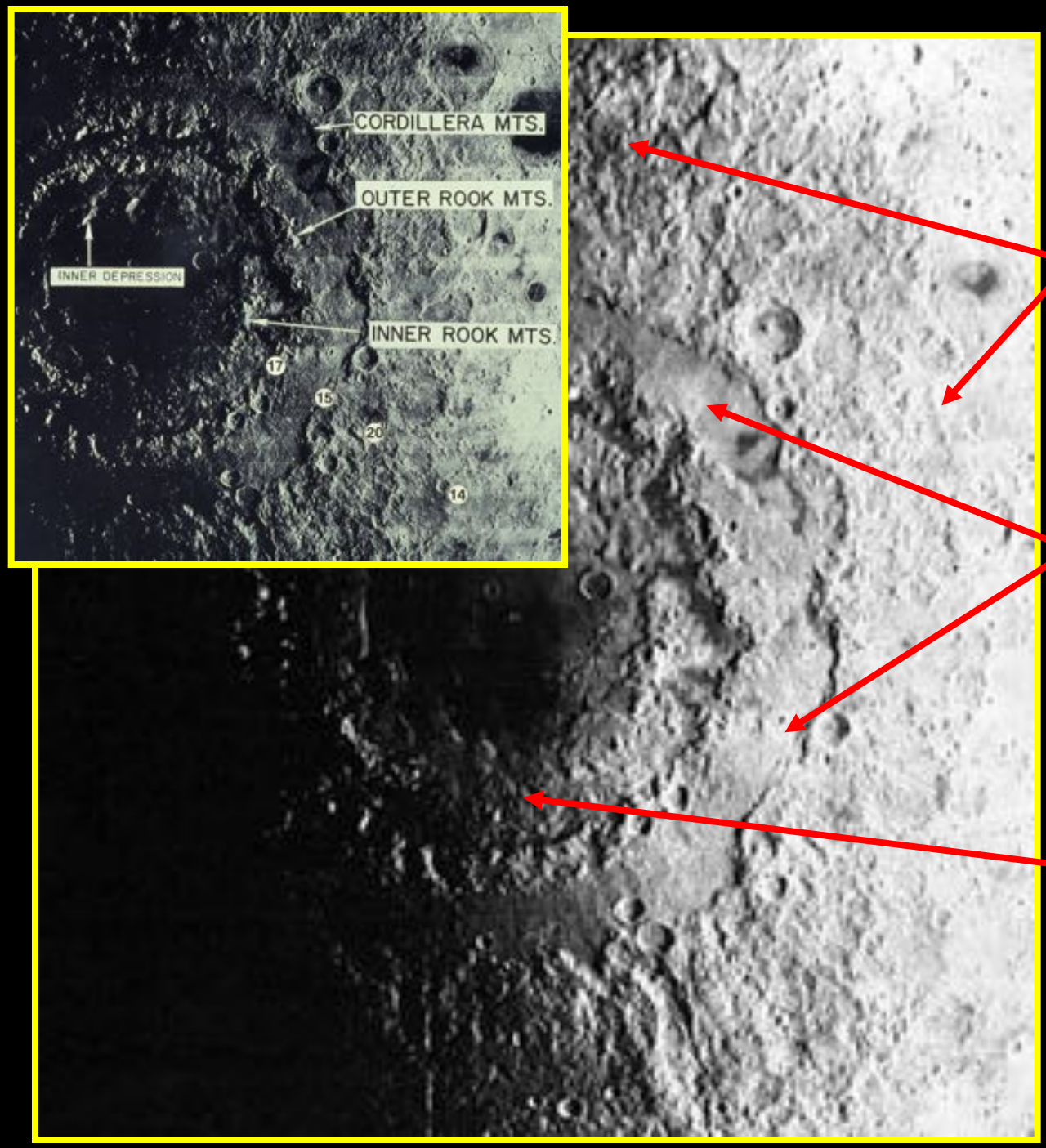
10
100

Crater Diameter (km)

(R. Pike)

# Lunar Orientale Impact Basin:
# The Type Area for Lunar Basin Formation and Evolution.






# Orientale Basin: Rings & Geologic Units

**Hevelius Formation**
**(Basin Ejecta Deposit)**

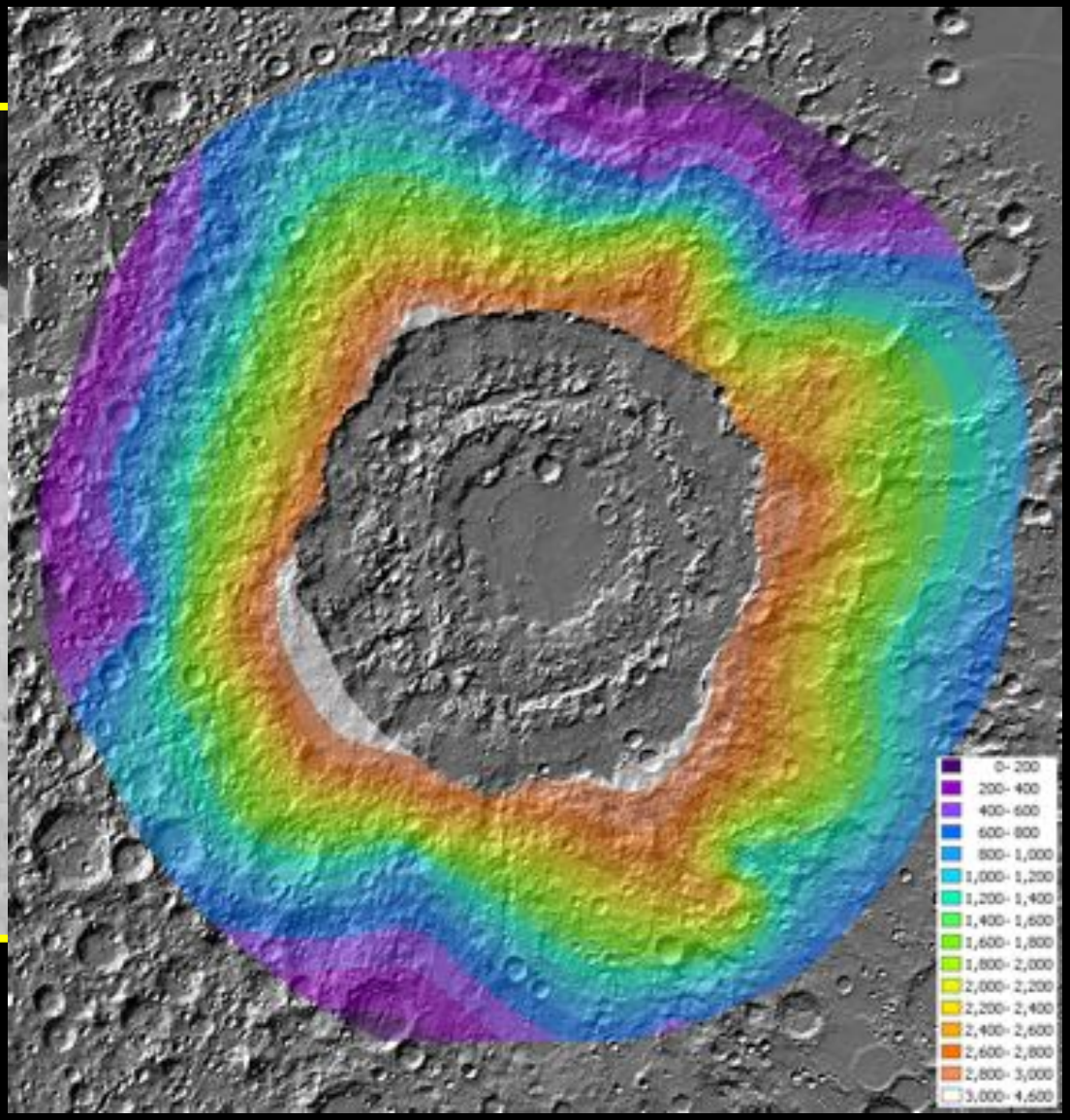
**Montes Rook Fm.**
**(Knobby, Domical Deposit)**

**Maunder Formation**
**(Basin Impact Melt Deposit)**

(J. McCauley, D. Wilhelms,
D. Scott, K. Howard, C. Hodges)

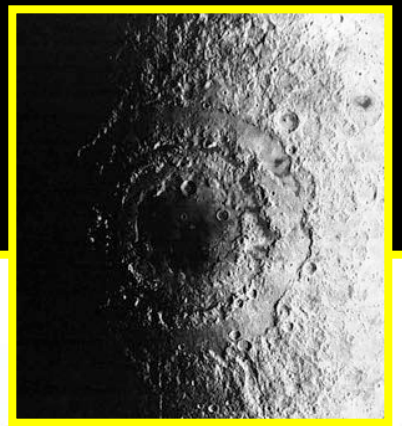
# Composition of the Ejecta from the Orientale Basin: Crust and Mantle

(Fassett and Head, 2011, GRL)




**Ejecta Thickness (Isopach) Map of the Hevelius Formation**

# Structure and Composition of the Lunar Crust: The Magma Ocean Model



Megaregolith
(~10 km thick)

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Upper Anorthositic Crust
(~15 km thick)

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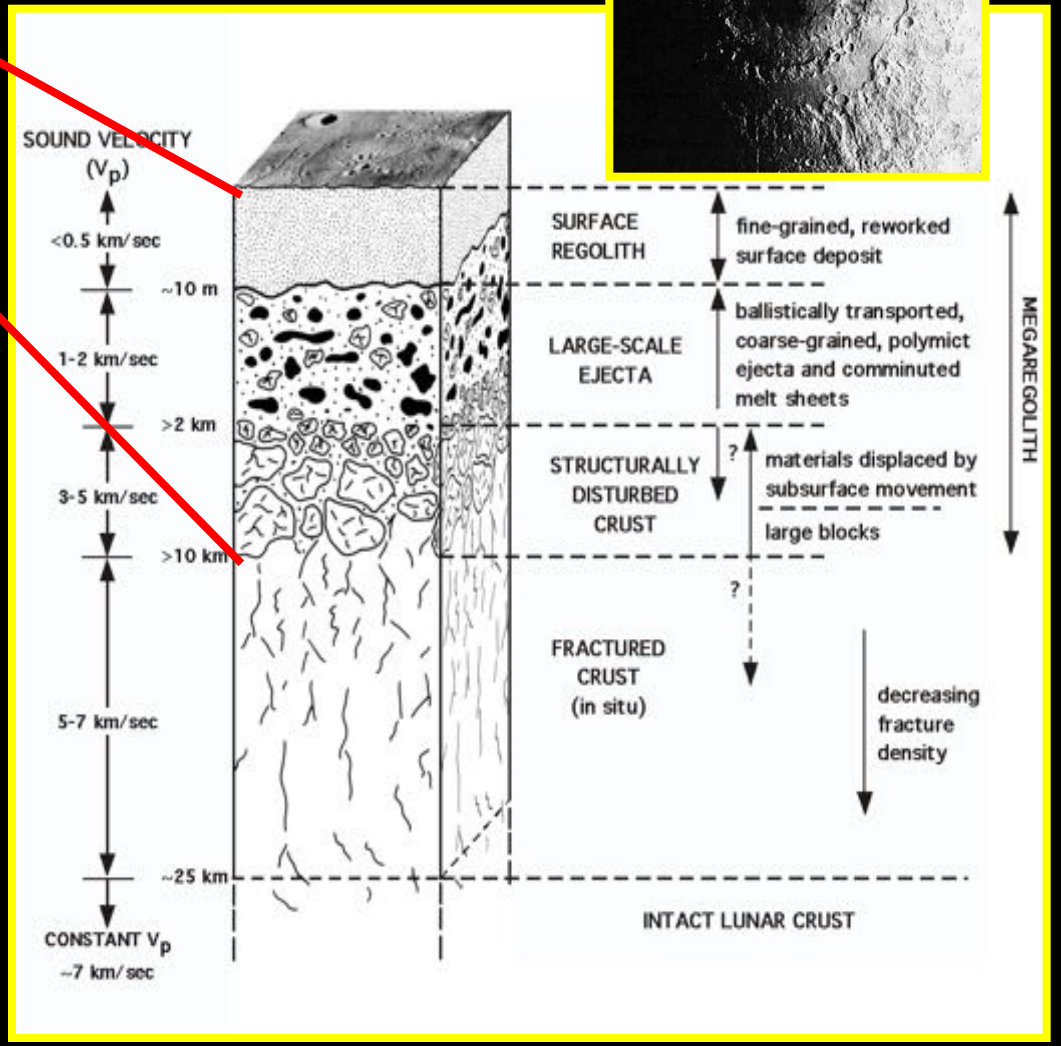
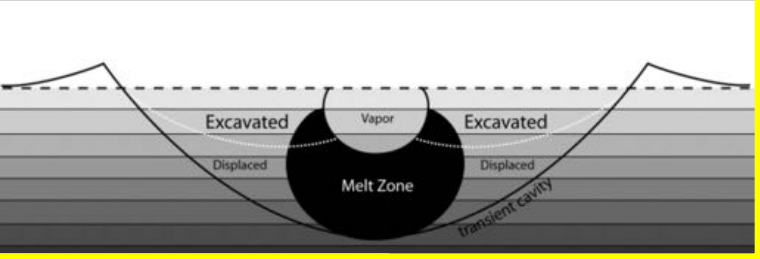
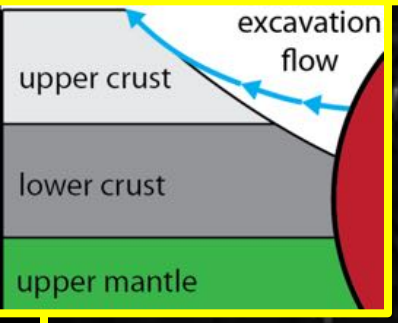
Lower Noritic Crust
(~25 km thick)




- Crust averages ~50 ±16 km thick.
- Upper and lower crust about equal.
- Upper crust heavily modified in the upper ~10 km by impact processes.




# Orientale Basin: Rings & Geologic Units

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**Hevelius Formation (Basin Ejecta Deposit)**
Feldspathic breccias; homogeneous, well-mixed.

**Cordillera Mountains:**
Feldspathic breccias; unweathered.

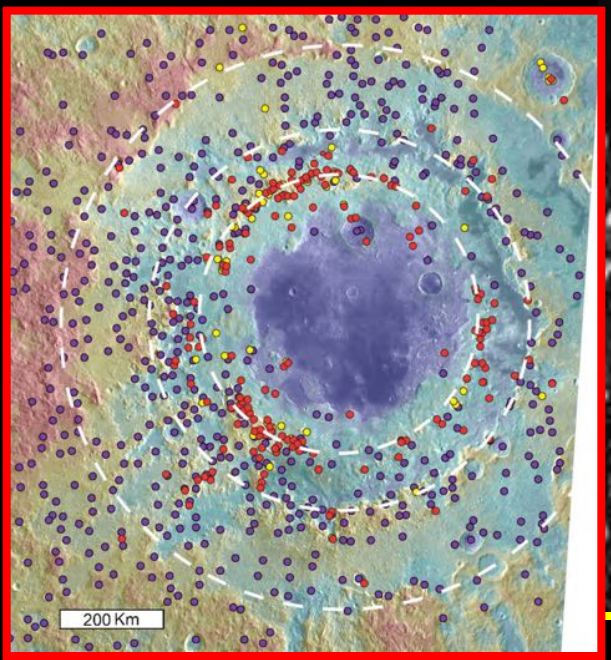
**Montes Rook Fm. (Knobby, Domical Deposit)**
Feldspathic breccias; some anorthosite blocks.

**Outer Rook Mountains:**
Norites, noritic anorthosite and anorthosite; more crystalline blocks.

**Inner Rook Mountains:**
Massifs are crystalline anorthosite; discrete peaks and clusters of peaks.

**Maunder Formation (Basin Impact Melt Deposit)**

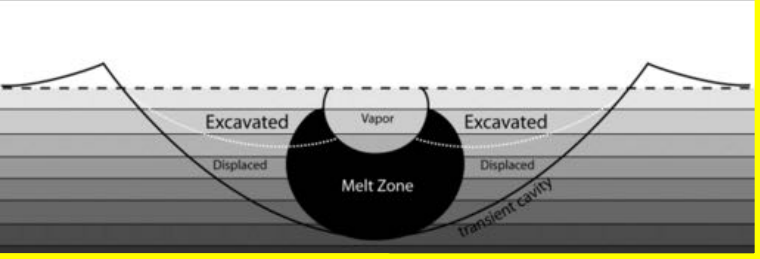
Moon Mineralogy Mapper (M3)

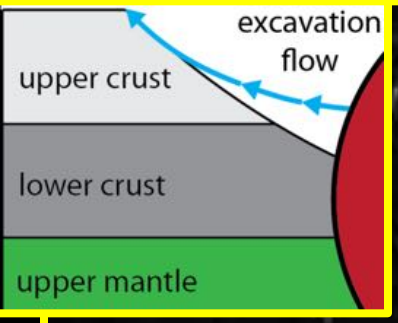


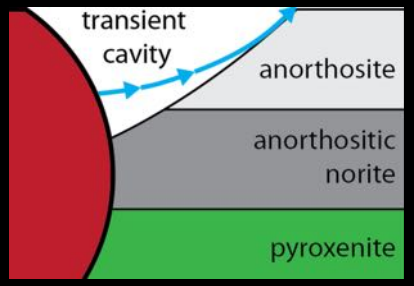

Red Dots (Inner Rook Mountains):
Materials >~98% plagioclase (Cheek et al., 2012)

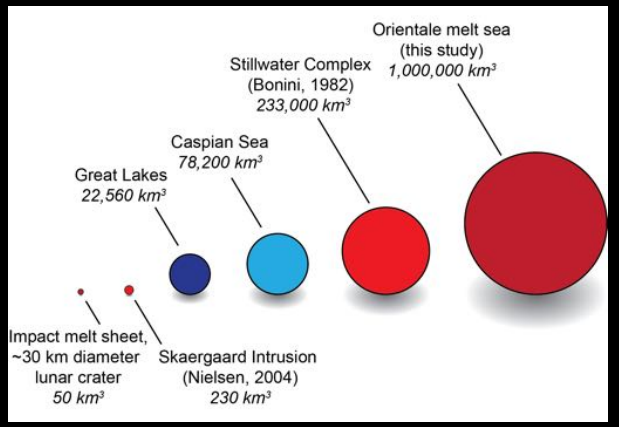
(Pieters et al., 2009, 2011; Head et al., 2010, 2012; Cheek et al., 2012)

# Orientale Impact Melt Sea



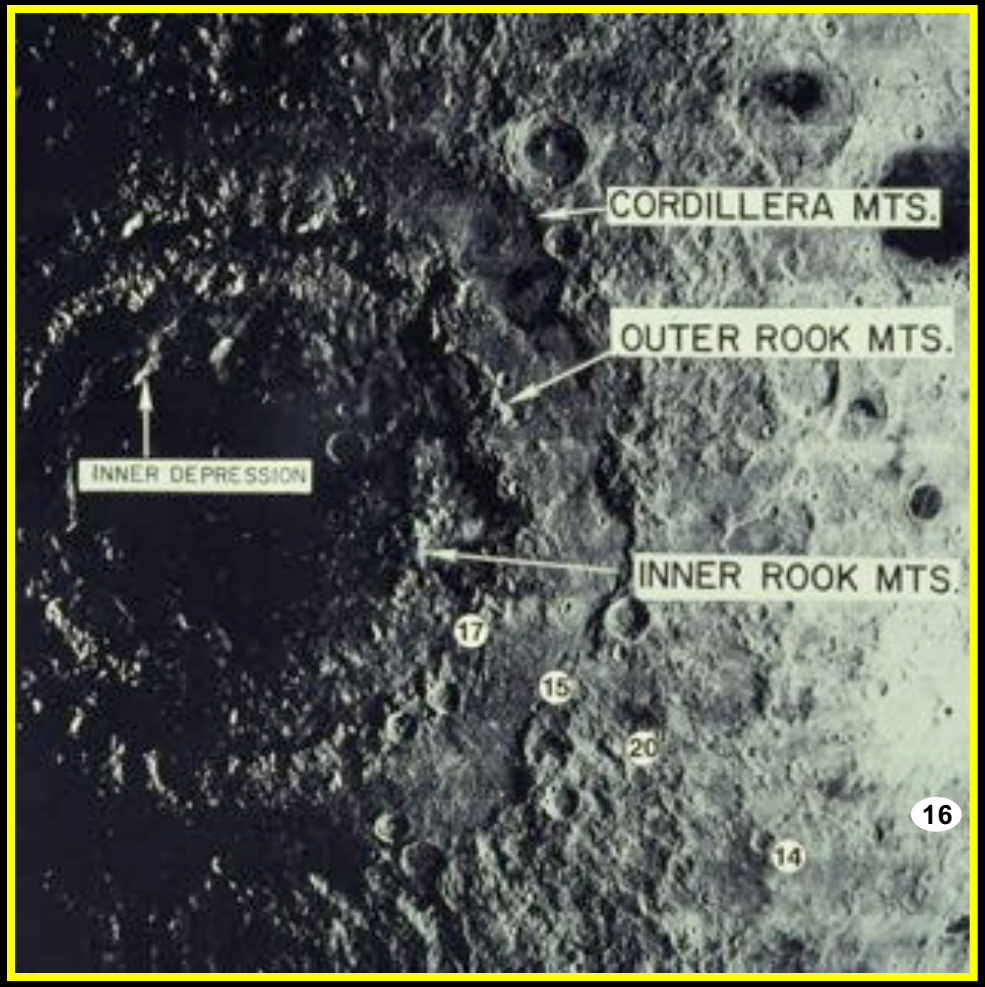



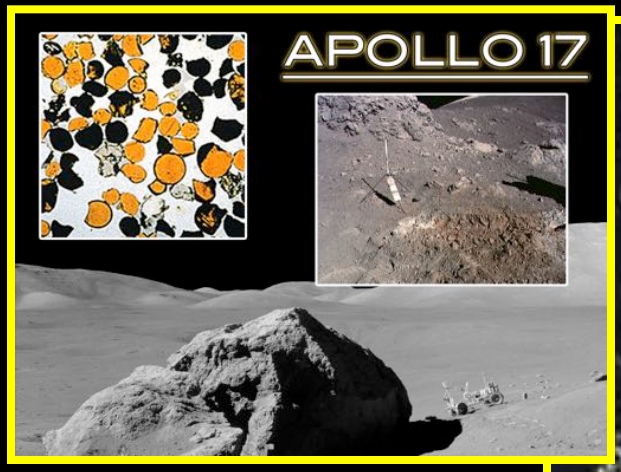

**Maunder Formation (Basin Impact Melt Deposit)**

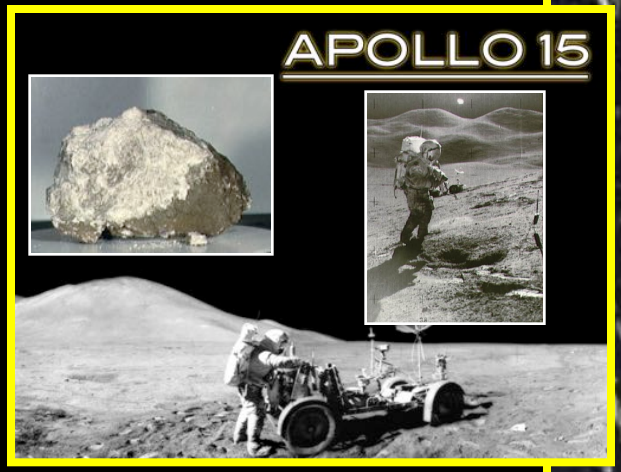
**(Wilson and Head, 2010; Vaughan et al, 2011, 2012; Spudis et al., 2014; Cassanelli and Head, 2016)**

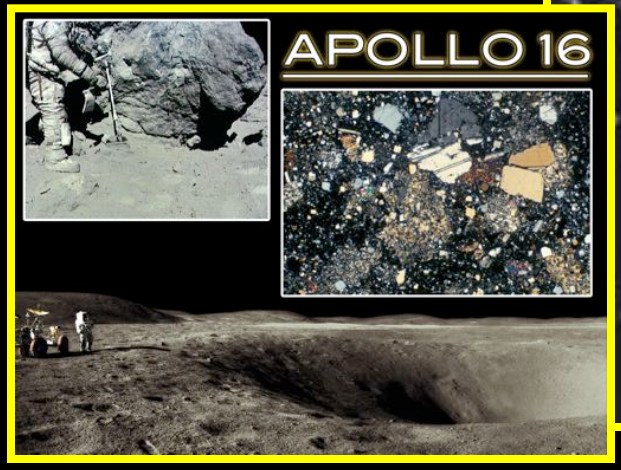
# Lunar Orientale Basin: Link to Apollo Missions Environments/Results



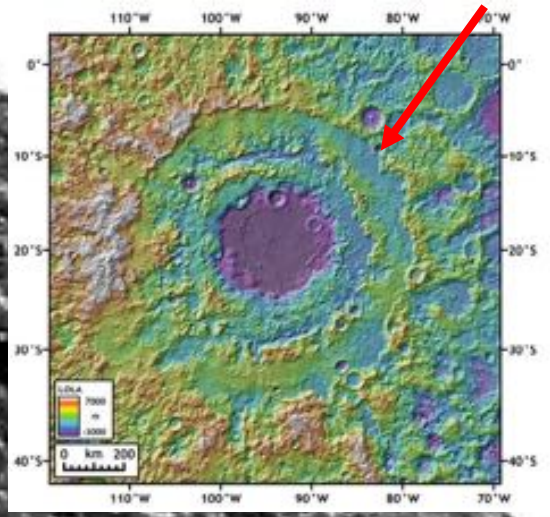


APOLLO 17

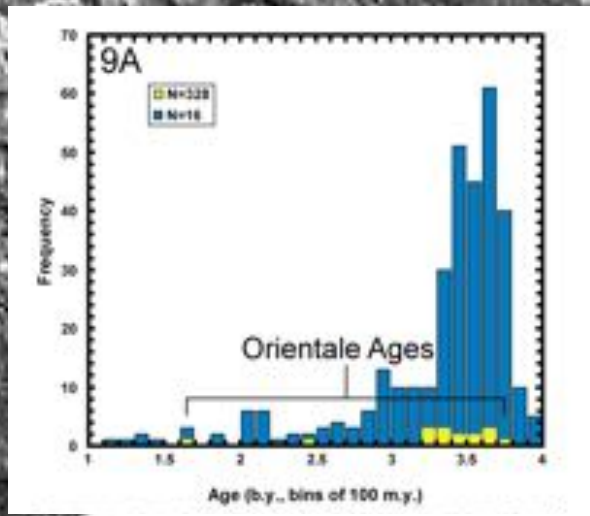

APOLLO 15


APOLLO 16


CORDILLERA MTS.
OUTER ROOK MTS.
INNER DEPRESSION
INNER ROOK MTS.
17
15
20
14
16

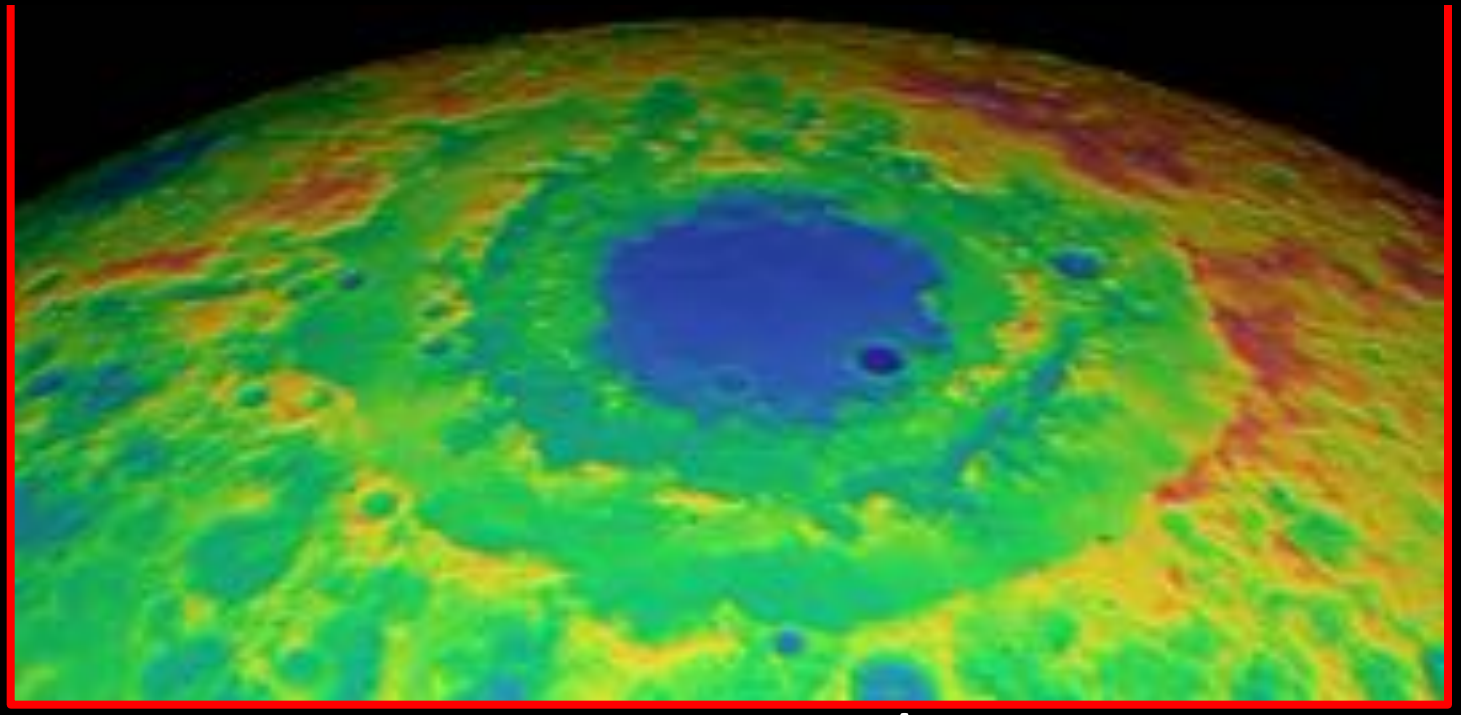
# Filling of the Orientale Basin with Mare Deposits.




(Whitten et al., 2010)

# Exploration of Planetary Crusts: A Human/Robotic Exploration Design Reference Campaign to the Lunar Orientale Basin



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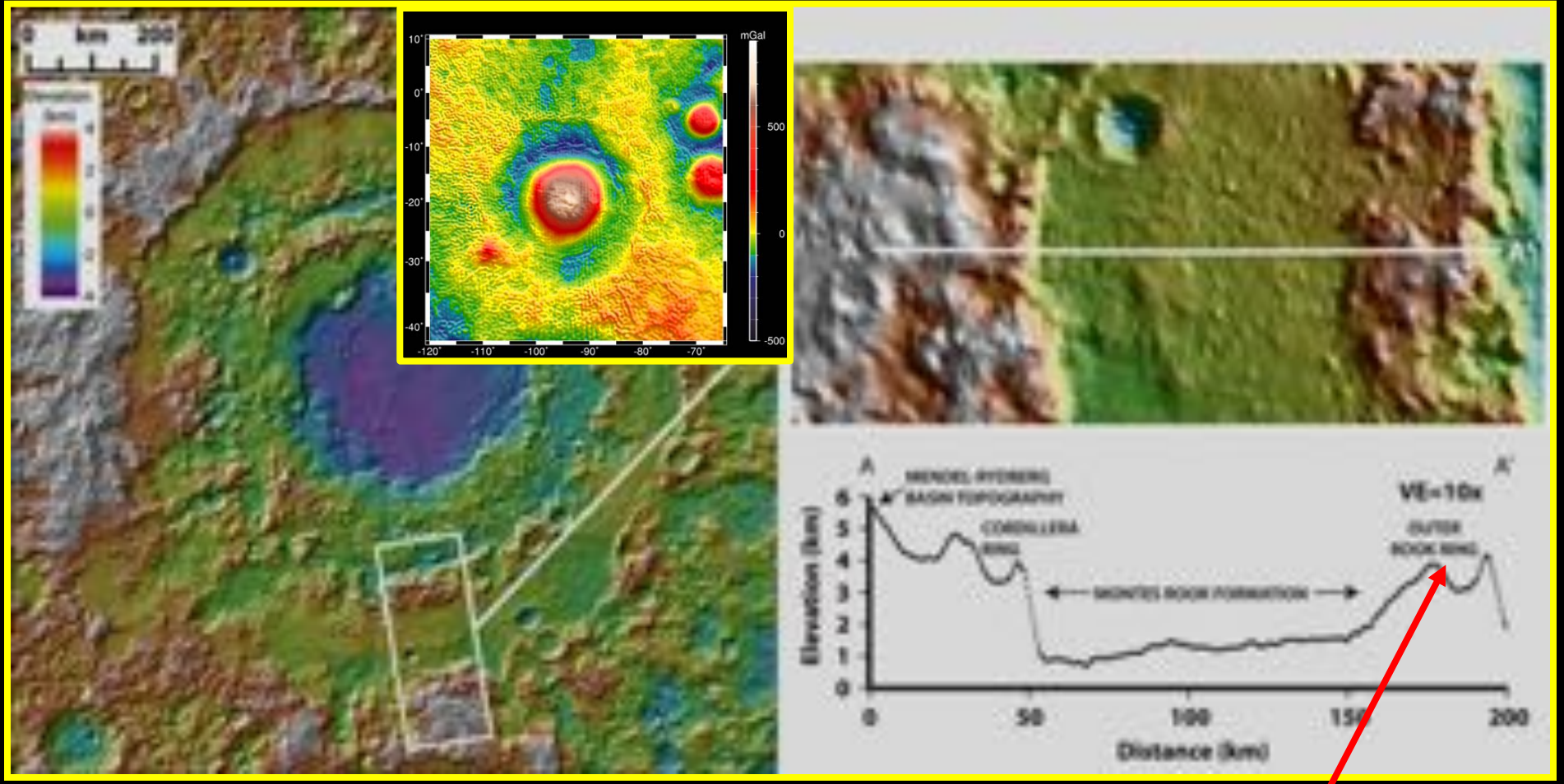
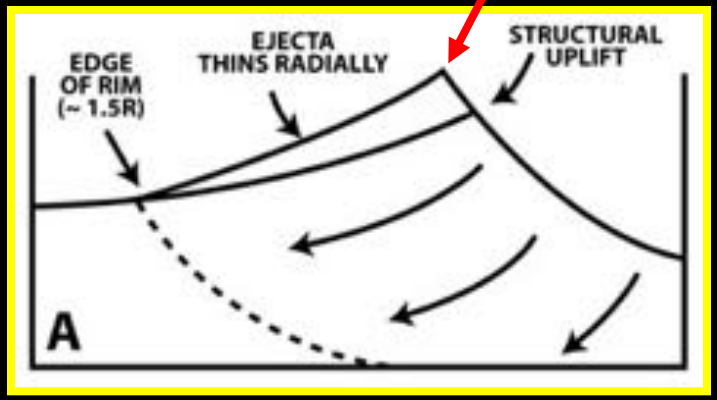
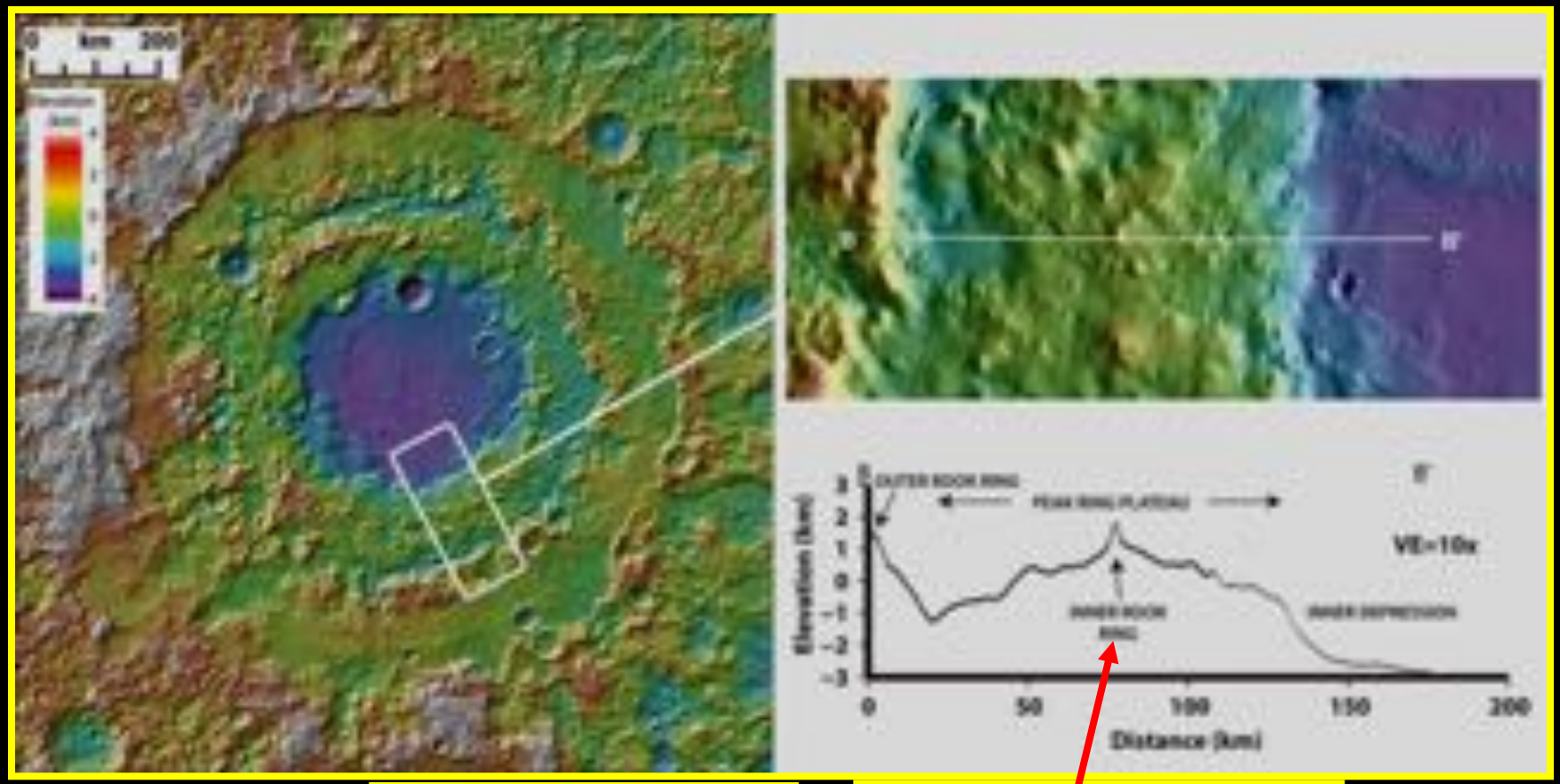


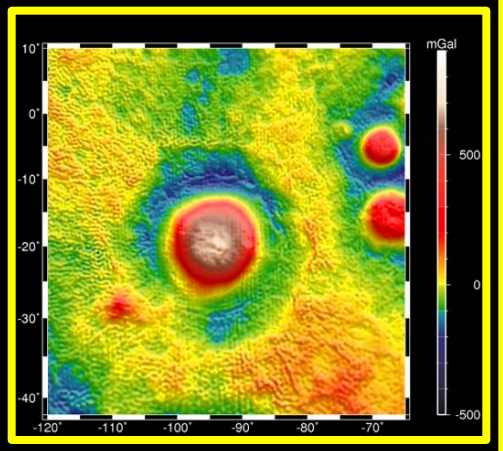

## Region of Interest (ROI) 1:
## Origin of Basin Rings/Crustal Structure

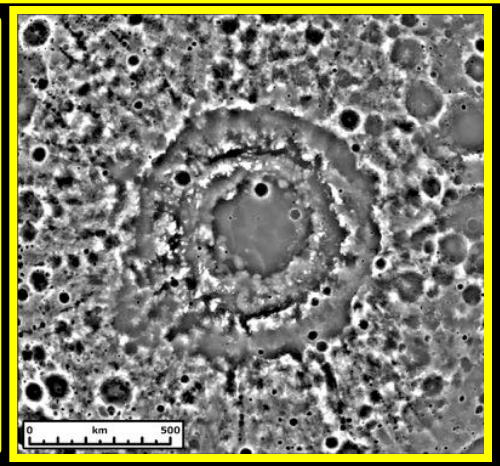
-If the Outer Rook ring represents the transient cavity rim crest, what is the origin of the Cordillera mountain ring and the Montes Rook Formation?

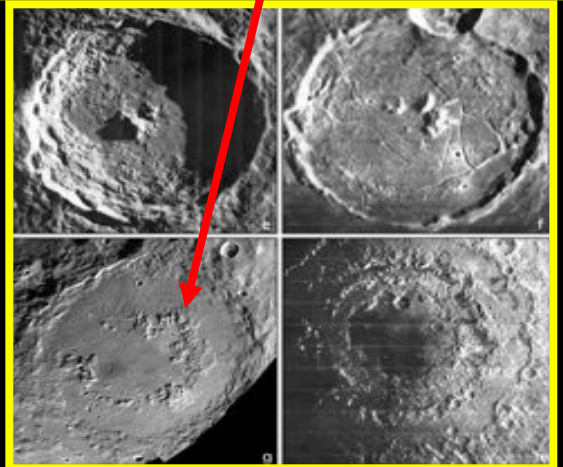


# ROI 2: What is the Origin of the Inner Rook Mountains?

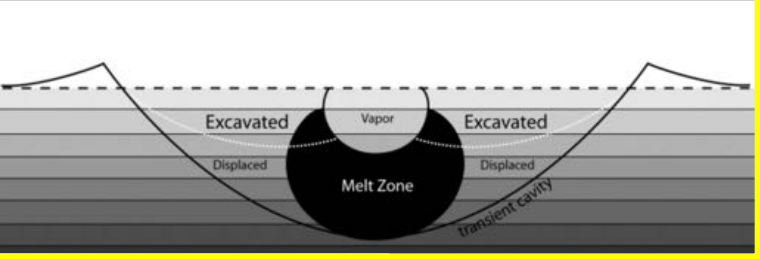


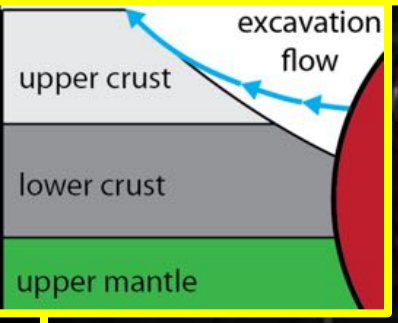



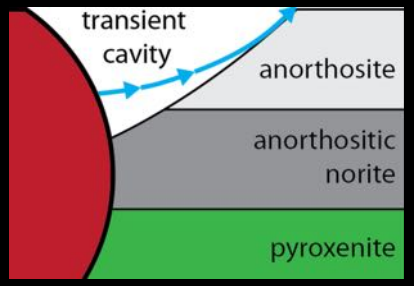



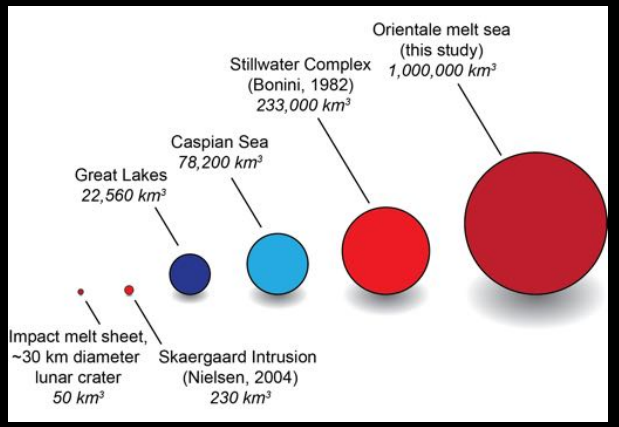



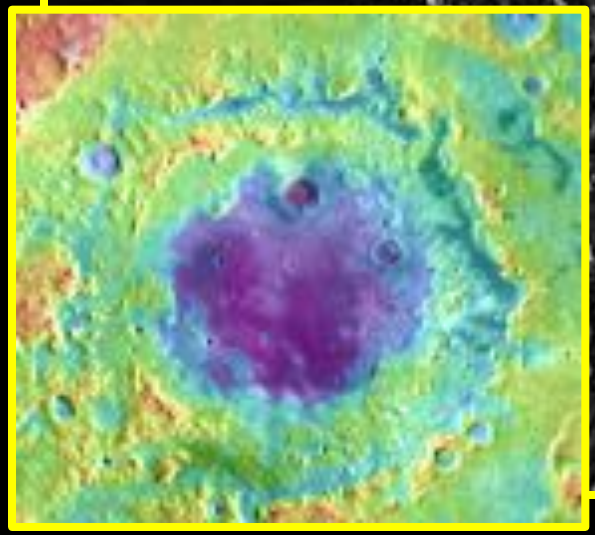
# ROI 3-Orientale Impact Melt Sea



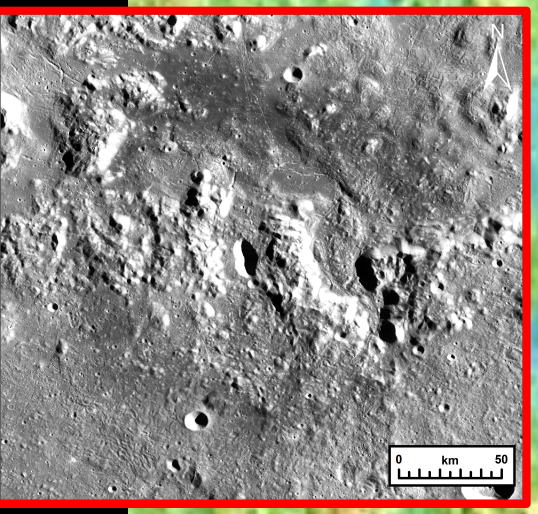



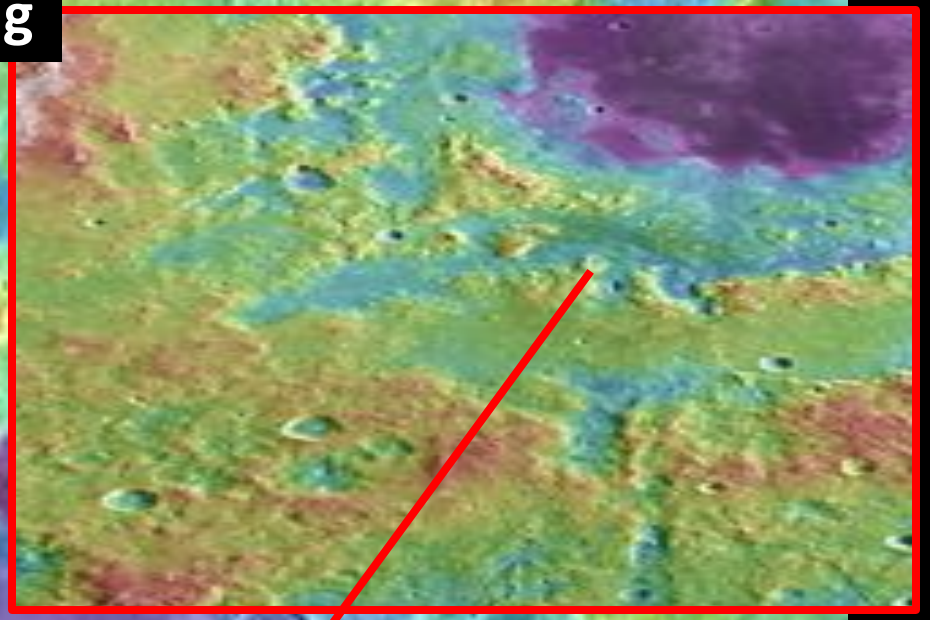



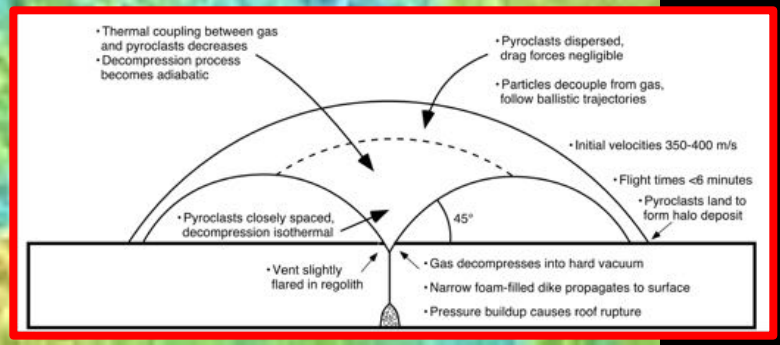
**Maunder Formation**
**(Basin Impact Melt Deposit)**

**(Wilson and Head, 2010; Vaughan et al, 2011, 2012; Spudis et al., 2014; Cassanelli and Head, 2016)**

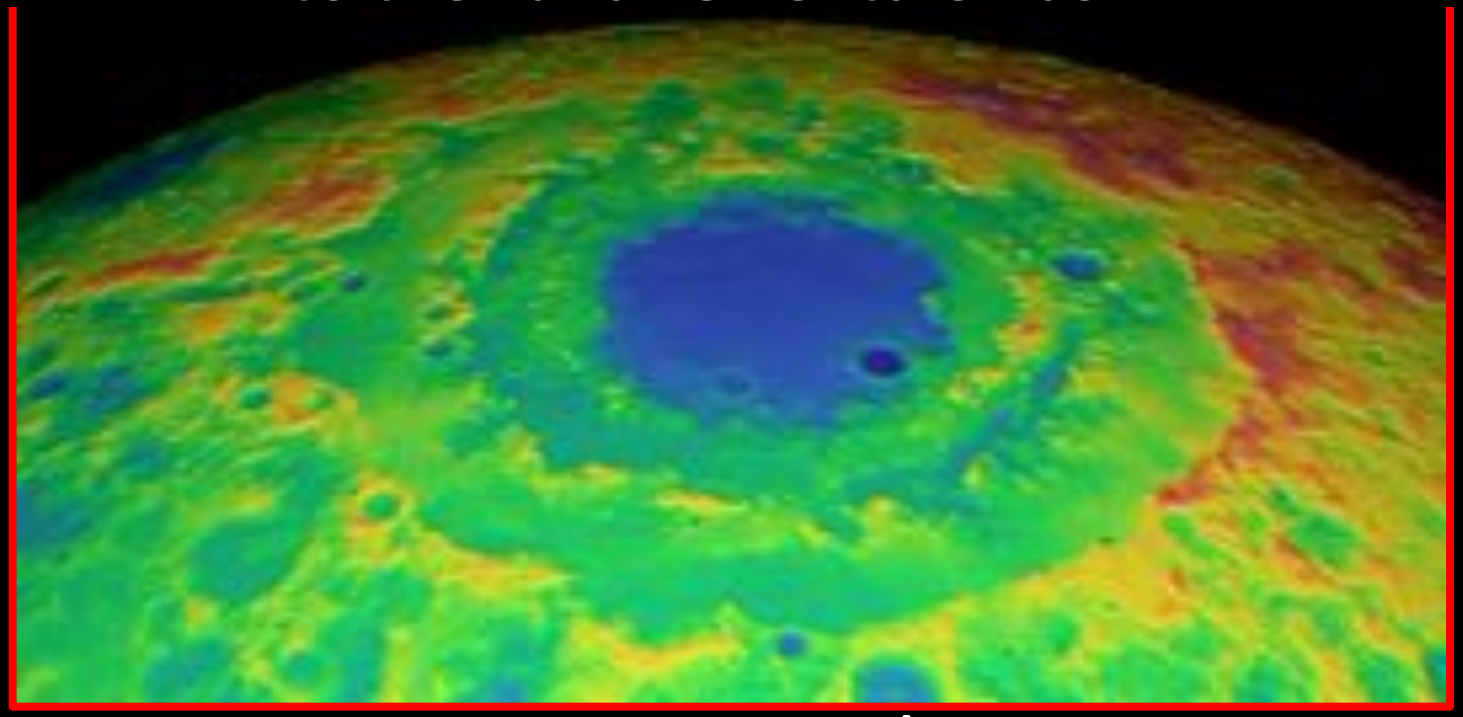
# ROI 4-Explosive Volcanic Ionian Ring



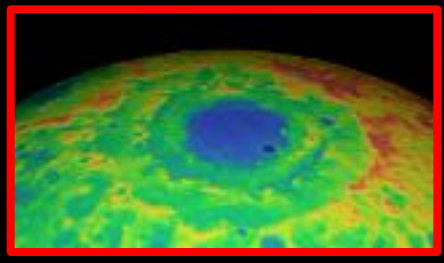


# Exploration of Planetary Crusts: A Human/Robotic Exploration Design Reference Campaign to the Lunar Orientale Basin



1. The importance of coordinated human/robotic exploration.
2. Why the Orientale multi-ring basin?
3. Human/Robotic Scientific Destinations at Orientale.
4. **The Human/Robotic Architecture: A Basis for Design Reference Missions.**

# Lunar Science for Landed Missions Workshop



- I) *Precursor* (What do we need to know before we send humans?).
- II) *Context* (What are the robotic mission requirements for final landing site selection and regional context for landing site results?).
- III) *Infrastructure/Operations* (What specific robotic capabilities are required to optimize human scientific exploration performance?).
- IV) *Interpolation* (How do we use robotic missions to interpolate between human traverses?).
- V) *Extrapolation* (How do we use robotic missions to extrapolate beyond the human exploration radius?).
- VI) *Progeny* (What targeted robotic successor missions might be sent to the region to follow up on discoveries during exploration and from post-campaign analysis?).